February 28th, 2018

Avoiding the Impossible: Re-focusing a Non-Feasible Mission 2-Hrs into a 3-Day Engineering Session

Thomas Youmans & Jairus Hihn

IEEE Aerospace Conference, 2018

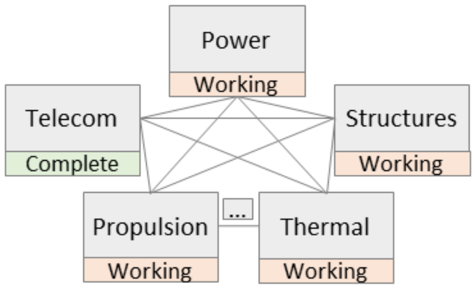
Big Sky, MT

Jet propulsion Laboratory/California Institute of technology

978-1-5386-2014-4/18/$31.00 ©2018 IEEE

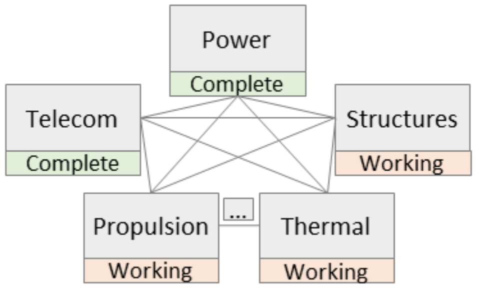
Concurrent engineering (CE) has demonstrated for over twenty years that it can produce high level mission designs in a short period of time, from months to only a few days. Unfortunately, sometimes these designs – while technically sound – are not feasible due to mass or cost constraints. A major new capability is needed by CE teams that will enable mission designers to re-focus a study, and avoid spending a great deal of time and effort with 15 engineers designing a non-feasible mission. The Jet Propulsion Laboratory's Team X is addressing this problem by developing mass and cost models that produce estimates for the probability of breaching a mass or cost threshold within the first hours of a study. These models are built on statistical relationships based on mass and cost allocations per mission component by mission type, derived from over twenty years of Team X studies and NASA missions. By linking these relationships, insights about total mass or cost can be made early in a study, based on preliminary requirements or the first completed spacecraft subsystem designs; estimates incorporate updated spacecraft subsystem designs as they are completed throughout the study. A methodology, generalized model, verification and example implementation for a cost limit breach are presented.

Fully understanding the system, structure of information, and processes flow in a concurrent design session is important for planning how models will ingest information, and determining which modeling methodologies are most appropriate [8].



Component	kg	Range	Source
Telecom	#	*+/- 5%*	*Eng Est, COTs parts*
Power	#	+/- 25%	Est by Typical Allocation
Structures	#	+/- 25%	Est by Typical Allocation
Propulsion	#	+/- 25%	Est by Typical Allocation
Thermal	#	+/- 25%	Est by Typical Allocation
Total	**#**		**Sum of estimates with distribution from var**

Figure 1: There are higher variance levels on the component estimates that are based on typical resource allocation percentages than engineering designs

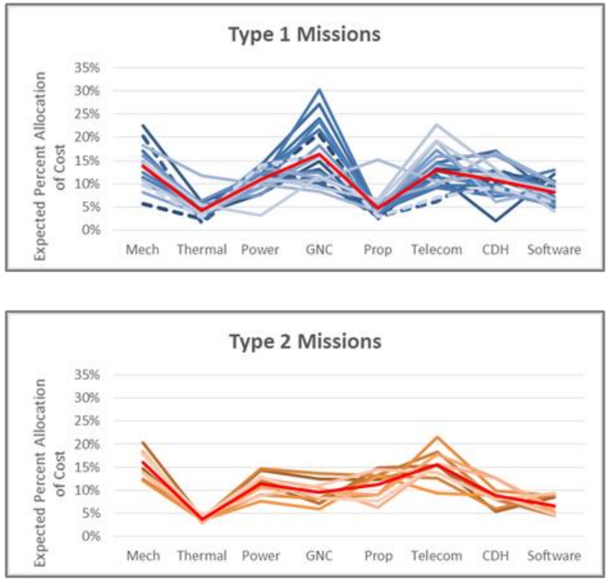


Component	kg	Range	Source
Telecom	#	*+/- 5%*	*Eng Est, COTs parts*
Power	#	*+/- 15%*	*Eng Est, Custom build*
Structures	#	+/- 25%	Est by Typical Allocation
Propulsion	#	+/- 25%	Est by Typical Allocation
Thermal	#	+/- 25%	Est by Typical Allocation
Total	**#**		**Sum of estimates with distribution from var**

Figure 2: When the telecom system is complete, known power needs inform the Power designer; power can't close before Telecom, and structures can't close before either; even though the power system has a closed design, it has a wider variance than the telecom system

The methodology presented in this paper is primarily based on typical resource allocations per mission and spacecraft component per mission type. This enables us to get rough, first order total mission and spacecraft costs and masses very quickly by taking a known mass or cost, combining that information with the typical allocation for that part of the spacecraft, and working backwards to get an implied total mass or cost of the spacecraft.

$$\frac{\textit{Payload Cost}}{\textit{Total Mission Development Cost}} = \begin{array}{c}\textit{Expected Percent} \\ \textit{Allocation of Cost} \\ \textit{for Payload}\end{array}$$



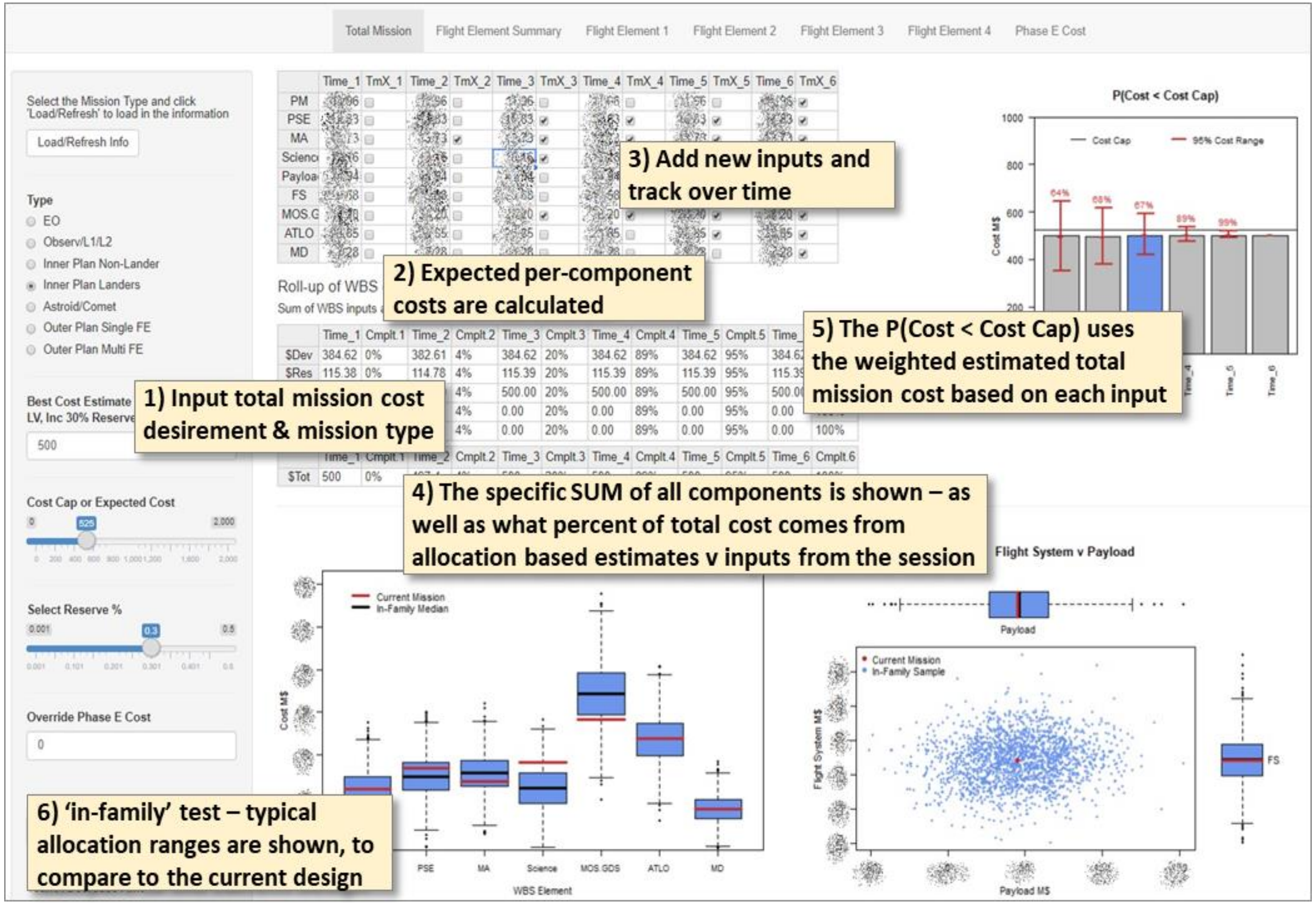
$$\begin{array}{c}\textit{Total Mission} \\ \textit{Development Cost Est}\end{array} = \frac{\textit{Payload Cost Est}}{\begin{array}{c}\textit{Percent Allocation} \\ \textit{of Payload Cost}\end{array}}$$

Figure 3: Determining Percent Allocation per component of total mission mass or cost is a very simple calculation, with major applications – especially when leveraging the differences in expected resource allocation per mission type; analysis shows distinct differences between mission types (2 of multiple shown)

In order to help design teams optimally use their time during concurrent engineering sessions by enabling them to refocus an non-feasible mission when working in a resource constrained environment, the key capabilities and outputs of the tools discussed in this paper are [5]

- Estimate resource allocations prior to the concurrent design session –
- Show expected allocation of resources
- Sum total current estimated mass or cost
- Calculate probability that the estimated resource stays beneath a given resource constraint
- Show whether the current design of the concurrent design session appears to be ‘in-family’ with typical missions of that type
- Test – “Are you leaving something on the table?” Examine if typical mission of your mission type and approximate total mass or cost used *more* mass or cost somewhere – that you’re leaving on the table

Using the data and statistical principles to accomplish the desired outputs within the constraints of the system



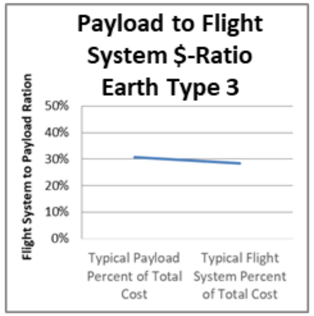
As described above, we would like to create a tool that has the ability to estimate the resources required for each component of a mission, estimate the resources of the total mission, estimate the probability that the total mission resources will break through a resource cap, and function with a varying number of available inputs [8].

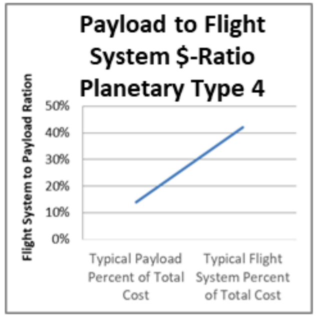
We have at our disposal data from previously flown missions, as well as from a number of completed mission studies. Separate analysis was performed outside of this paper that indicates that the data from the mission studies is highly similar to the data from the actual missions. In the analysis presented, data from actual missions and highly detailed mission studies was merged together in order to meet data needs for the analysis.

The components that we'd like to have estimates for include: total mission, flight system, each flight element within the flight system, payload, each Work Breakdown Structure (WBS) line item for the mission, and each Subsystem of the flight system; when a flight system includes multiple flight elements, we'd like to have a resource breakdown for each subsystem of each flight element [10].

As discussed above, we will avoid using parametric models, and will focus on a version of analogy based estimation – defining our analogous missions, or 'groups of similar missions' or 'mission types' by looking for similar resource allocations or similar trends in resource allocation per group, and different resource allocations among different groups. This is accomplished using a mixture of subject matter expertise and quantitative methods. The typical resource allocations give us key relationships between the components of a mission [14].

An embodiment of the methodology presented to determine the probability of a resource breaking through a resource cap as updated inputs are used is shown, followed by examples of using the expected percent allocations of cost applied within additional key tools.





INPUTS: PL + FS or Tot Cost	
FS+PL $M	-
Tot A-D Cost	$495
Mission Type	Earth 3
% Reserves	30%
OUTPUTS: A-D, $M FY16	
PM	$12
PSE	$12
MA	$12
Science	$20
Payload	$150
FS	$140
MOS/GDS	$20
ATLO	$10
Mission Design	$5
Reserves	$115
Total	$495

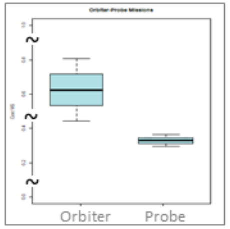
INPUTS: PL + FS or Tot Cost	
FS+PL $M	-
Tot A-D Cost	$495
Mission Type	Planetary 4
% Reserves	30%
OUTPUTS: A-D, $M FY16	
PM	$12
PSE	$12
MA	$12
Science	$15
Payload	$80
FS	$200
MOS/GDS	$25
ATLO	$15
Mission Design	$10
Reserves	$115
Total	$495

Figure 5: Fast cost breakouts allow mission designers to investigate payload capacities for different architectures

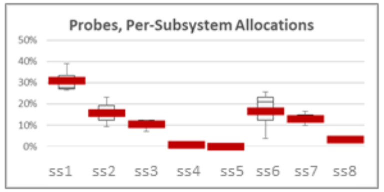
Total Cost: $500M
Mission Type: Outer Planetary Multi Flight Element

INPUTS: PL + FS	
FS+PL $M	-
Tot A-D Cost	$500
Mission Type	Outer Planetary Mx FE Type 5
% Reserves	30%
OUTPUTS: A-D, $M FY16	
PM	$15
PSE	$15
MA	$15
Science	$10
Payload	$75
FS	$200
MOS/GDS	$25
ATLO	$18
Mission Design	$12
Reserves	$115
Total	$500

The per WBS Breakdown indicates that we get $200M for the total Flight System



The per Flight Element Breakdown indicates that we get 30% of our $200M Flight System for the Probe, yielding $60M



For more detail, we can apply the Probe Subsystem allocations to the $60M

Figure 6: Applying percent allocations shows how much we may expect to spend on the probe – can we build the probe for that cost figure? We can test for feasibility here; specific numbers have been edited

The backbone of the methodology presented is typical resource allocation profile per component of a mission – which provides us with the key relationships per mission component. We need these typical allocations or trends in allocations to be consistent within each ‘type’ of mission, and we would expect them to be different across different types of missions. For example – we would expect a $500M Earth Orbiter to spend a higher percent of its total budget on the instrument suite (payload) than the percent of total budget we would expect a Mars Lander mission to spend on its instrument suite.

In order to understand all of the pieces of analysis necessary for the methodology presented, we will discuss them individually:

- Estimate expected resource allocations
- Estimate total needed resources from subcomponent inputs
- Discussion of variance
- Sample the total cost estimates
- Weight and combine the total cost estimates
- Find the probability of breaking a resource cap
- Identify different ‘types’ of missions - examine different mission types to look for differences in key relationships within mission cost and mass (allocations)
- Key focus of separating missions by type - the major defining factors that were used in determining the different ‘mission type’ groups for this analysis were
- Resulting mission types with distinct key allocations

Key Focus of Separating Missions by Type

Looking for separation of 'types' of mission by focusing on consistent resource allocations or trends in resource allocation is the optimal method for the methodology presented, as this method optimally minimizes the difference in allocation of resources per mission component within each distinct mission type grouping. By minimizing the variation in per mission component allocation, we get a more accurate and precise estimate of the resources required for each component of the mission, and a more accurate and precise estimate for the total resources needed for a mission. This methodology doesn't *force* differences in resource allocation per mission component across different groups, but it does optimally separate out mission types with different per component allocations from each other.

It is important to examine trends in resource allocation per mission type as well – as some resource allocations will vary depending on the total size or cost of a mission, *within* a given type of mission. Different types of missions will have resource allocation percentages that change in different ways, so it is important to include the change in resource allocation per mission component, when determining the different type of missions.

For example – the percent allocation of total cost that the Payload gets for Earth Orbiters **increases** as the total cost of the mission cost increases – because generally, it only takes a certain amount of money to get your mission into Earth's orbit, and then the rest of your money can go towards a more expensive instrument. If you have $250M, you may need to spend $150M to get to Earth's orbit and stay there, whereas if you have $500M, you may need to spend $150M to get to Earths orbit, but now you have $350M out of $500M instead of $50M out of $200M for your instrument suite (note: if your instrument suite increases in cost or mass, there are typically increases in your flight system, but for the purposes of this example, Earth Orbiter Payload is shown to *not be a constant* percent of total mission cost). However, consider a Mars Lander – if your payload increased by even $10M, you know that you'll have more mass to land on Mars, so you know that as your Payload costs increase, you can expect your flight system costs to increase as well – so perhaps the percent of total mission cost that goes to payload does *not* increase as your total mission cost increases (or more specifically, it does not increase as much as it does for other mission types).

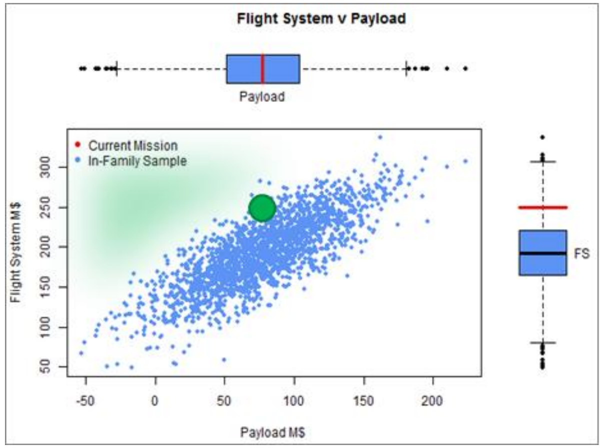


Figure 7: If Flight System funding is high relative to the Payload, there is a lower Flight System cost growth risk

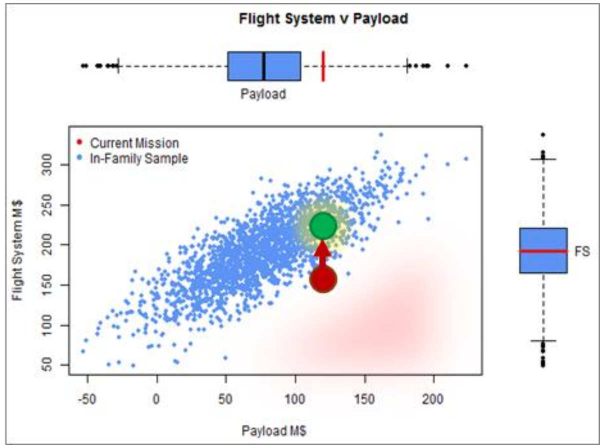


Figure 8: If Flight System funding is low relative to the Payload, there is a higher Flight System cost growth risk

We are interested in the typical resource allocations for all components of a mission, but there are some components that give us the most important information, and drive the mass and cost of the total mission. Payload to flight systems relationships, and Payload + Flight System to total mission relationships – per mission type – are the most important relationships in our system.

Spacecraft Cost-Growth Risk

The area where mission mass or cost growth risk usually materializes is in the spacecraft. Whether it's due to changing payload requirements, or an ambitiously designed and costed spacecraft – this is where mass and cost growth happens. By having a good understanding of typically required spacecraft resources needed for a given payload, mission designers can understand their mass and cost growth risk profile [12].

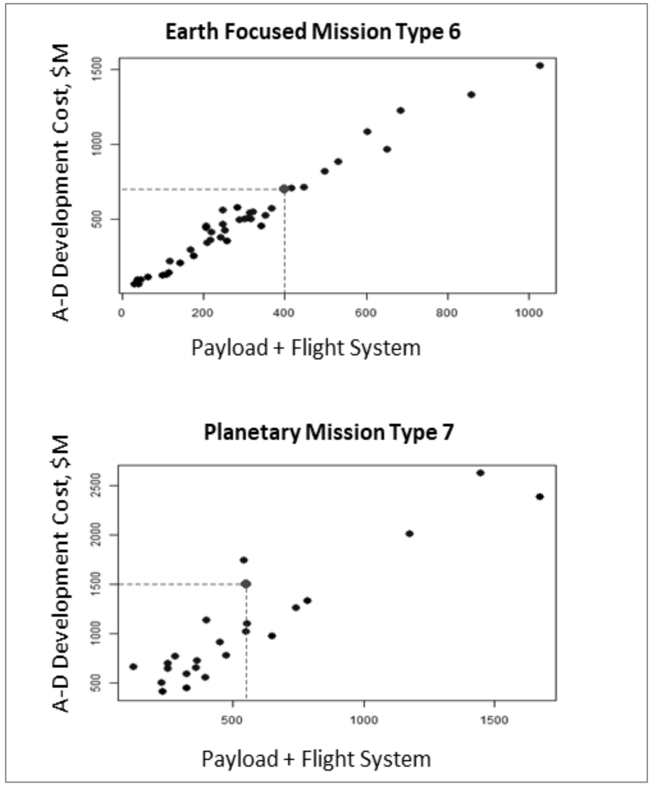


Figure 9: There are solid relationships between total mission A-D development cost and Payload + Flight System cost; a mission that is being designed is can be examined to test if it appears to be 'in-family'

The sums of the inputs at Time_1 though Time_6 are all the same, but P(Cost < Cost Cap) are not

	Time_1	TmX_1	Time_2	TmX_2	Time_3	TmX_3	Time_4	TmX_4	Time_5	TmX_5	Time_6	TmX_6
PM	13.24	☐	13.24	☐	13.24	☐	10.24	☐	13.24	☐	13.24	☐
PSE	13.68	☐	13.68	☐	13.68	☐	10.68	☐	13.68	☐	13.68	☐
MA	17.11	☐	17.11	☐	17.11	☐	14.11	☐	17.11	☐	17.11	☐
Science	12.74	☐	12.74	☐	12.74	☐	9.74	☐	12.74	☐	12.74	☐
Payloa	62.99	☐	72.99	☐	102.99	☐	122.99	☐	62.99	☐	62.99	☐
FS	210.22	☐	200.22	☐	170.22	☐	170.22	☐	210.22	☐	210.22	☐
MOS.G	28.19	☐	28.19	☐	28.19	☐	25.19	☐	28.19	☐	28.19	☐
ATLO	17.36	☐	17.36	☐	17.36	☐	14.36	☐	17.36	☐	17.36	☐
MD	9.07	☐	9.07	☐	9.07	☐	7.09	☐	9.07	☐	9.07	☐

Roll-up of WBS costs

Sum of WBS inputs and auto-populated WBS estimates

	Time_1	Cmplt.1	Time_2	Cmplt.2	Time_3	Cmplt.3	Time_4	Cmplt.4	Time_5	Cmplt.5	Time_6	Cmplt.6
$Dev	384.62	0%	384.61	0%	384.61	0%	384.62	0%	384.62	0%	384.62	0%
$Res	115.38	0%	115.38	0%	115.38	0%	115.39	0%	115.38	0%	115.38	0%
$A-D	500.00	0%	500.00	0%	500.00	0%	500.01	0%	500.00	0%	500.00	0%
$E	0.00	0%	0.00	0%	0.00	0%	0.00	0%	0.00	0%	0.00	0%
LV	0.00	0%	0.00	0%	0.00	0%	0.00	0%	0.00	0%	0.00	0%
	Time_1	Cmplt.1	Time_2	Cmplt.2	Time_3	Cmplt.3	Time_4	Cmplt.4	Time_5	Cmplt.5	Time_6	Cmplt.6
$Tot	500	0%	500	0%	500	0%	500.01	0%	500	0%	500	0%

Based on the methodology presented, we can see that increasing Payload funding and decreasing Flight System and management funding decreases our probability of staying within our cost cap

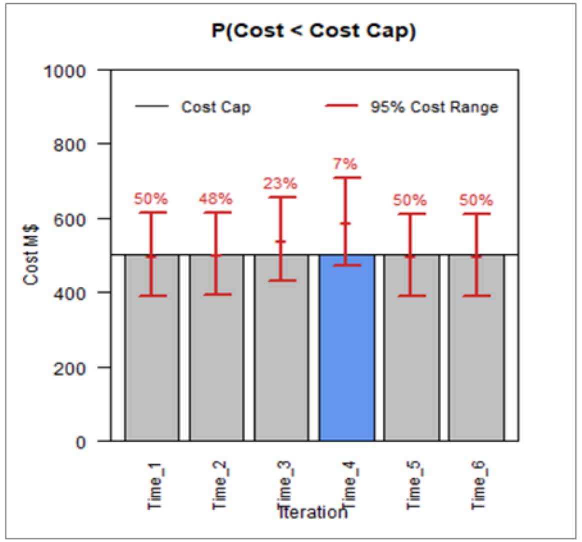


Figure 10: The methodology presented penalizes missions for having very unusual cost allocations, this helps the design team be aware of risks that are not evident when only looking at the sum of the components

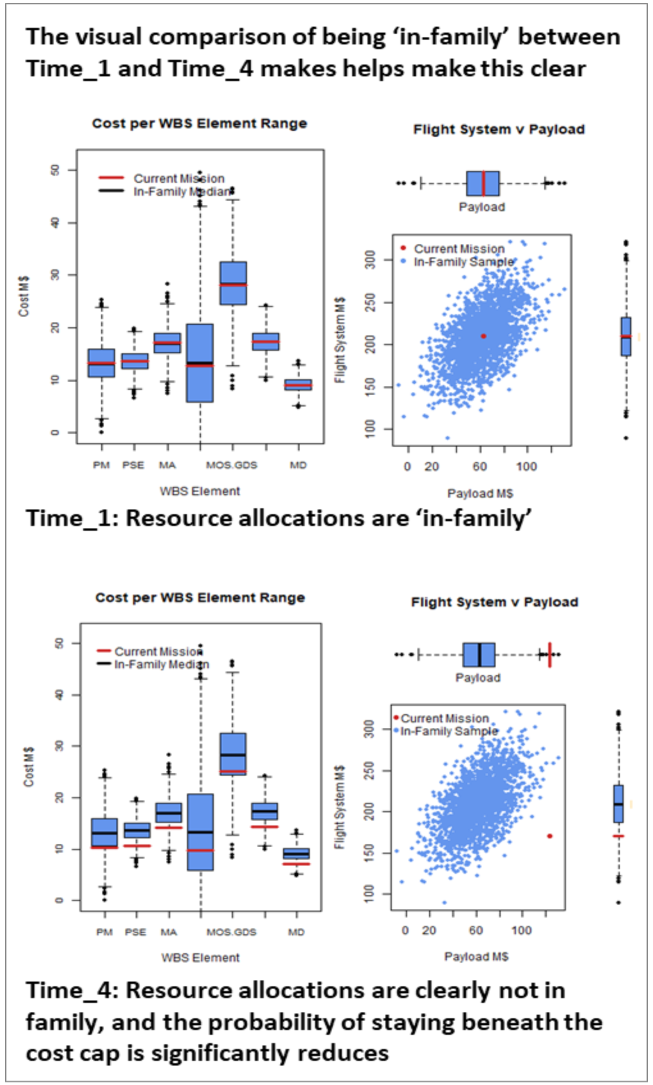


Figure 11: Clear visual warnings about being 'out-of-family' help designers stay aware of what's happening during lively design sessions

ACKNOWLEDGEMENTS

This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

DISCLAIMER

The cost information contained in this document is of a budgetary and planning nature and is intended for informational purposes only. It does not constitute a commitment on the part of JPL and/or Caltech.

REFERENCES

[1] Wall, S., “Use of Concurrent Engineering in Space Mission Design.” *EuSEC 2000 Proceedings*. Munich, Germany, 2000.

[2] Kluger, J. and Cray, D., “Management Tips from the Real Rocket Scientists.” *Time*. Nov. 2005.

[3] Karpati, G., Martin, J., Steiner, M., and Reinhardt, K., “The Integrated Mission Design Center (IMDC) at NASA Goddard Space Flight Center.” *IEEE Aerospace Conference 2003 Proceedings*. Big Sky, MT, 2003.

[4] McGuire, M., Oleson, S., Babula, M., and Sarver-verhey, T., “Concurrent Mission and Systems Design at NASA Glenn Research Center: The origins of the COMPASS Team.” *AIAA Space Conference 2011 Proceedings*. Long Beach, CA, 2011.

[5] Mulqueen, J., Hopkins, R., Jones, D., “The MSFC Collaborative Engineering Process for Preliminary Design and Concept Definition Studies.” *AIAA Space Conference 2011 Proceedings.* Long Beach, CA, 2011.

[6] Bandecchi, M., Melton, B., Gardini, B., and Ongaro, F., “The ESA/ESTEC Concurrent Design Facility”, *Proceedings of 2nd European Systems Engineering Conference (EuSEC 2000).* Munich, Germany, 2000.

[7] Warfield, K., and Hihn J., “Spreadsheets in Team X: Preserving Order in an Inherently Chaotic Environment.” *42nd Hawaiian International Conference on System Sciences (HICSS 42) Proceedings.* Waikoloa, HI, 2009.

[8] Morse, E., Leavens, T., Cohanim, B., Harmon, C., Mahr, E., and Lewis, B., “Next-generation concurrent engineering: Developing models to complement point designs,” *IEEE Aerospace Conference 2006 Proceedings.* Big Sky, MT, 2006.

[9] Zarifian, P., Imken, T., Matousek, S., E., Moeller, R. C., et. al., “Team Xc: JPL's collaborative design team for exploring CubeSat, NanoSat, and SmallSat-based mission concepts.” *IEEE Aerospace Conference 2003 Proceedings*. Big Sky, MT, 2015.

[10] Hihn, J., Chattopadhyay, D., ADD NAMES et. al., “Aerospace Concurrent Engineering Design Teams: Current State, Next Steps and a Vision for the Future.” *AIAA Space Conference 2011 Proceedings*. Long Beach, CA, 2011.

[11] Moeller, R. C., Borden, C., Spilker, T., Smythe, W., Lock, R., “Space Missions Trade Space Generation and Assessment using the JPL Rapid Mission Architecture (RMA) Team Approach.” *IEEE Aerospace Conference 2011 Proceedings*. Big Sky, Montana, 2011.

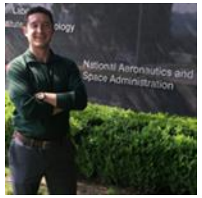
[12] Rhodes, D. H., Valerdi ,R., and Roedler G. J., “Systems Engineering Leading Indicators for Assessing Program and Technical Effectiveness.” *Systems Engineering.* vol. 12, no. 1, pp. 21-35, 2008.

[13] Manuele, F. A., “Leading & Lagging Indicators.” *Professional Safety.* vol. 54, no. 12, pp. 28–33, 2009.

[14] Garthwaite, P. H., Jolliffe, I. T., Jones, B., *Statistical Inference.* Oxford University Press, 2006.

[15] Akhundov, J., Werner, M., Schaus, V., Gerndt, A., “Using timed automata to check space mission feasibility in the early design phases.” *IEEE Aerospace Conference 2003 Proceedings*. Big Sky, MT, 2016.

BIOGRAPHY



Thomas Youmans *is a Systems Engineer and Data Scientist at NASA's Jet Propulsion Laboratory. Thomas received his Master of Science in Mathematics & Statistics from Georgetown University, and his Bachelor of Arts in Physics and Economics from Lewis & Clark College. Thomas supports early mission formulation through statistical modeling, operations and technical design through data analysis, and deep space mission proposals through systems engineering. Previously, Thomas served with the Peace Corps in Bulgaria, and worked in market research consulting for investor due diligence, and government consulting with the Department of Energy.*

Jairus Hihn *(PhD University of Maryland, 1980) is a principal member of the engineering staff at the Jet Propulsion Laboratory, and is currently the leading a laboratory wide cost improvement task. He has been developing estimation models and providing software and mission level cost estimation support to JPL's and NASA since 1988.*